EXTENDING THE 3-OMEGA METHOD TO THE MEGAHERTZ RANGE FOR MEASURING THE THERMAL CONDUCTIVITY OF DIAMOND THIN FILMS

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Abstract

Knowing the thermal conductivity of a material is important for the successful design and implementation of any thermal management application. A special challenge however is the experimental determination of the thermal conductivity of highly thermal conductive materials such as diamond, which are synthesized in the form of thin films. Not only may the thin film's thermal conductivity significantly differ from well-established literature values for the bulk material. It may also strongly depend on the particular synthesis conditions. For example, chemical vapor deposited diamond thin films exhibit a wide process depending range of microstructures with crystal dimensions from a few nanometers to several hundreds of micrometers. The grain boundary density and therefore potential sites for thermal wave scattering vary accordingly.

With diamond thin films becoming increasingly important for high-power and high-speed electronics applications we are developing an experimental technique to measure the thermal conductivity of these films. One such technology is the so-called 3-Omega method [1]. This method can be applied to measure the thermal conductivity of dielectric materials and requires depositing a conductive pattern to the surface of the film, which may be accomplished via a lithographic process. For example, in our case we use a 5 nm chromium interface to promote the adhesion of a 200 nm silver layer. Applying a lift-off masking process, structures were generated as shown in Fig.1.

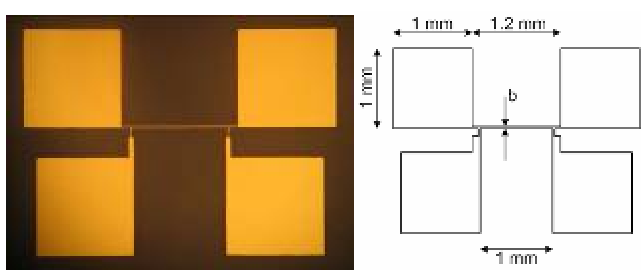

Fig.1 Heater / thermometer electrode structures

The metal pattern consist of a thin line (5 – 20 µm, depending on lithographic capabilities) functioning as heater/thermometer, whereas the 1 mm^2 large squares serve as contact pads.. The, for the analysis necessary, dR/dT curves of the heater/thermometer structures are measured by applying a 2.5ºC/min temperature ramp up to 150ºC. The values are recorded during rising and falling temperatures and the procedure is repeated twice for each sample to ensure that the samples are properly annealed.

A current at the angular frequency ω is applied to the thin line, which generates a temperature oscillation ΔT at a frequency of 3ω. The driving frequency dependence of this temperature oscillation can be determined by measuring the first and third harmonic voltages, the dR/dT curve and the average resistance of the heater/thermometer. The thermal conductivity of the dielectric material can then be determined by fitting the solution of the appropriate heat conduction equation to the experimental data. For the particular geometry of a thin heater/thermometer line Cahill [1] developed an efficient method to allow for a straight forward linear approximation.

However, this linear approximation is limited to the lower frequency range (up to kHz, depending on material), where the penetration depth of the thermal wave is significantly larger than the width of the heater/thermometer. Simultaneously the penetration depth of the thermal wave, which is proportional to the square root of the thermal conductivity, has to be smaller than the film thickness to avoid substrate effects. These conditions can be summarized as follows:

$$\text{line width} << s = \sqrt{\frac{\lambda}{i\omega\rho C}} << \text{film thickness} \quad (1)$$

Expression (1) illustrates the difficulties that arise for measuring thin and highly thermal conductive films. Keeping the thermal penetration depth *s* smaller than the film thickness requires using higher frequencies ω, which in return requires an even smaller line width. For example, a 5 µm diamond film would require more than 8 MHz to keep the thermal penetration depth just under 5 µm, and the heater/thermometer should be much narrower than 5 µm, which makes it more difficult to produce.

In this paper we address the specific challenges of the method for measuring highly conductive thin films by extending the applied frequency into the MHz range as well as analyzing the measured data beyond the low frequency limit by fitting to the complete solution of the thermal conductivity equation rather than to the linear fraction of it. Fig. 2 demonstrates the capability of the setup for SiO_2 measurements.

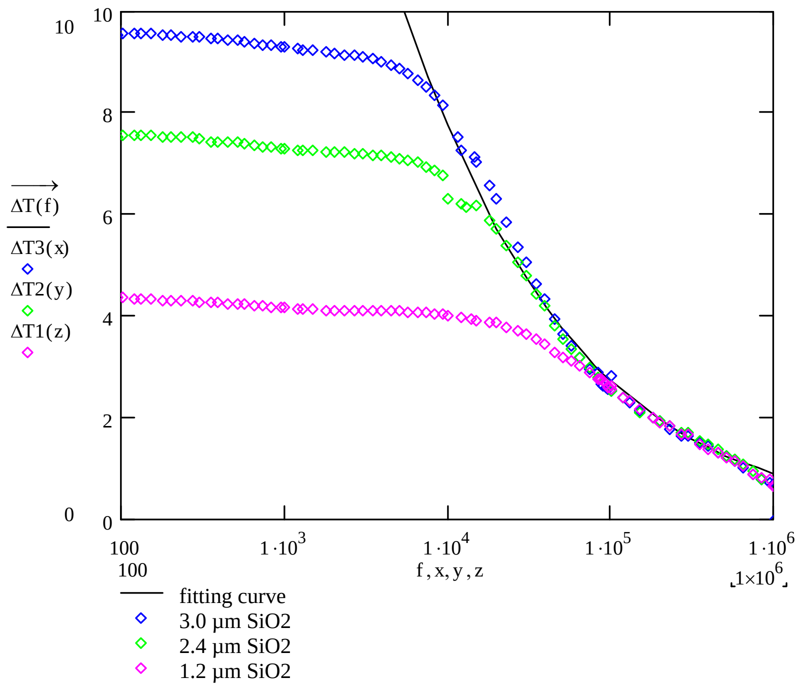

Fig. 2 Temperature versus frequency for SiO2 films on silicon

The SiO2 layers shown above demonstrate the capability of our set-up to measure up to 1 MHz driving frequency. The three SiO2 films of different thicknesses (1.2 µm, 2.4 µm and 3.0 µm) indicate that the thermal conductivity (λ = 1 W/(m K)) is independent of film thickness.

Our current driving frequency limit of 1 MHz is determined by the cable length between the probes and the compensating measurement circuitry. Currently we are measuring diamond films as thin as ≈ 15 µm. A redesigned probing head is under development and will enable to apply this 3-Omega technique to even thinner diamond films.

REFERENCES

1. D. G. Cahill, Thermal *conductivity measurement from 30 to 750 K: the 3w method,* Ref. Sci. Instrum. 61(2), 802 (1990).